The Design and Construction of the Electronics Package

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The electronics system of the Telstar satellite is described from the point of view of philosophy of design and construction rather than that of circuit details. The reliability is emphasized, and steps taken to preserve the inherent reliability of the components are discussed. The physical construction of modules, subsystems, and finally the entire system is described, including the foam encapsulation and the eventual hermetic sealing of the canister.

I. INTRODUCTION

The reliability program of the Telstar satellite is based upon three factors: component reliability, conservative circuit design with few innovations, and rugged equipment design with quality construction insured by specially trained craftsmen and extensive inspection. Wherever possible, past experience with proven reliable systems provided a guide when applying these factors. In contrast to the approach used in many other satellite programs, the Telstar spacecraft contains a minimum of redundancy. It is also unusual in that the mechanical design encloses most of the electronic circuitry in a hermetically sealed canister filled with polyurethane foam. This prevents readjustment and unit replacement; however, it provides a very rugged unit which is safe from tampering. To further enhance reliability, "white room" conditions were observed during all construction stages.

II. COMPONENTS[1]

Component reliability, together with redundancy, sets an upper limit on the reliability of the system, for the circuit designer can at best preserve the inherent level of reliability built into the components furnished to him. The selection of semiconductor types was based upon proven reliability in previous systems. A large number of units of a single type

were tested, and those used in the spacecraft were obtained by choosing the best — about 33 per cent of the total number tested. These tests consisted of operating each unit at a controlled power dissipation or exposing each unit to a controlled amount of radiation while observing the degradation against time of such properties as gain, voltage breakdowns and leakage currents. To further improve reliability, deratings of approximately ten to one were typically used with respect to power rating, voltage breakdowns and leakage current.

The types of passive components used were also chosen for their proven reliability in previous systems. In addition, each component was individually tested before use. The passive components used were not a selection of the best of a large group, as with the semiconductor devices, but those components which passed the tests. This provided, in most cases, a better than 90 per cent yield from those tested. Derating factors of at least two to one were used with respect to power ratings and voltage breakdowns to improve reliability. All other special components were carefully examined and tested to insure good over-all component reliability.

The careful screening of components means that the construction program of circuit modules, subassemblies, and entire canisters need not be based on having large numbers from which to select the best units. This results in the electronic circuit tests being utilized chiefly to find design errors and interface incompatibilities.

III. CIRCUIT DESIGN

Reliable circuit operation is obtained by minimizing the need for new inventions; by basing the circuit design on well established methods; and by including in the design as much margin as power consumption, size, and weight will permit. In the case of microwave design, the Bell System has a great fund of knowledge which has been built up over the years with the two transcontinental microwave systems, the TD-2 and TH systems, operating at 4 and 6 gc respectively. Since both of these frequencies are used in the Telstar project, it was possible to follow earlier designs of such equipment as filters and frequency converters. Similarly, years of Bell System experience in designing circuits for operation from dc to very-high-frequency form a basis for development in these areas.

During the circuit development stages, the circuits were temperature cycled between $-20°C$ and $+60°C$. Circuits with components which would be severely affected by these temperature extremes were given as wide a temperature test as their components would allow. The mini-

mum design temperature range is 0°C to +40°C. To be acceptable, a circuit was required to operate completely satisfactorily within the design temperature limits and to operate with little loss in performance between the −20°C to +60°C temperature limits. Groups of circuits were also exposed to these temperature tests to investigate circuit interface problems.

As early as possible the circuit was wired into its first equipment layout form and foamed to assure proper operation in its final environment. It was then given vibration tests with vibration magnitudes equal to or greater than those specified in the satellite qualification test specification.[2] These requirements were more stringent than the conditions expected during handling and launching. Those circuits which would normally operate during the launch were electrically tested during the vibration test. Circuits not expected to be operational during the launch phase, such as the microwave circuits, were electrically tested for survival only.

Following the design of a circuit, a computer analysis was used, time permitting, to investigate the effects of variations in active and passive components which would result from temperature effects, aging, and initial tolerances. A variational study permitted the investigation of "worst-worst" conditions.

IV. EQUIPMENT DESIGN, CONSTRUCTION, AND TEST

The equipment design used in the Telstar satellite is conservative and is based when possible on past experience. No microminiaturization is utilized, but rather the usual methods associated with microwave and lower-frequency circuits have been used. To aid in explaining the equipment design approach, an example of the construction and evaluation process in the form of a regulator will be described in some detail.

The initial step in the production of a unit such as the regulator is the compiling of the necessary components. As described in a companion paper,[1] each component is serialized before being delivered to the assembly area. Clerical personnel assemble all the necessary components for a particular circuit into a kit and record the serial number of each component, together with the location of that component in the circuit. This careful record keeping on devices can be of considerable value in diagnosing failures. A case in point is the command circuit malfunction in the satellite.[3] In this case, once the transistor which caused the malfunction was determined, it was possible to review that transistor's original characteristics.

Certified wiremen with special training then assemble the circuit.

Special precautions were observed when the more delicate components were handled. Operators handling point-contact semiconductor devices wore grounded bracelets, and those handling units with critical finishes wore white nylon gloves. Fig. 1 shows the completed wiring of one of the boards making up the regulator. The miniature magnetic latching relays used for controlling the traveling-wave tube are shown together with a number of passive components. Much thought was put into the type of mechanical structure and the type of electrical connections employed in such boards to assure the necessary mechanical and electrical reliability.[4] Upon completion of wiring, the board shown in Fig. 1 is sent to the inspectors.

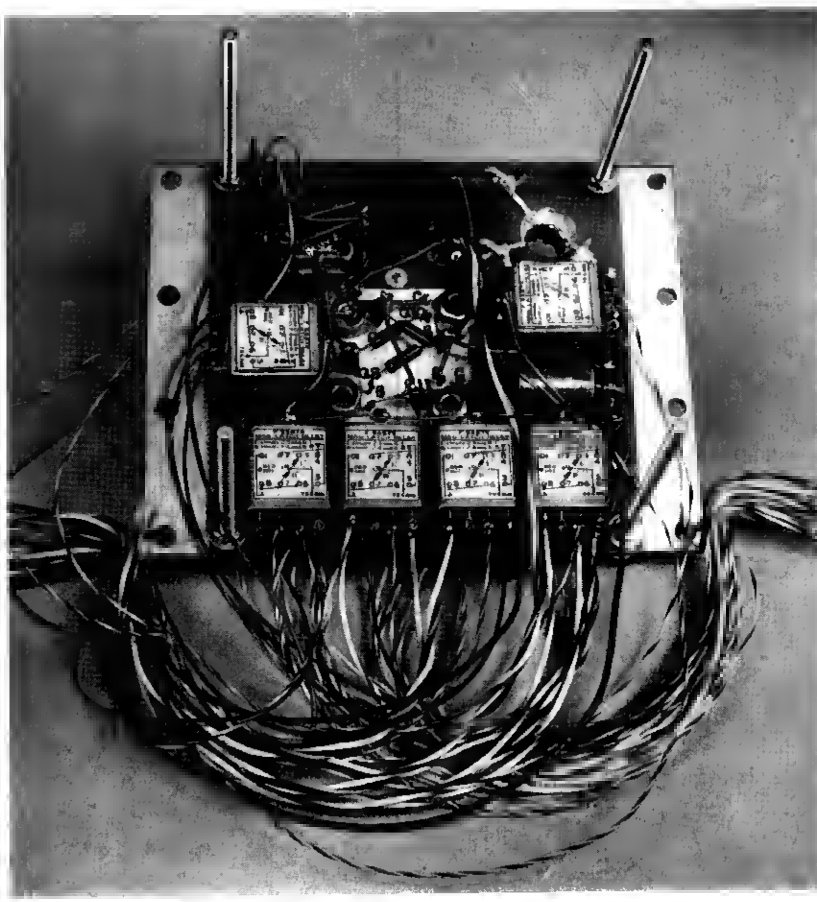

Fig. 1 — First circuit board of regulator.

Visual inspection plays an important part in assuring mechanical reliability. The Bell System's experience in the development of the submarine cable repeaters, where an equal or greater degree of mechanical reliability was necessary, had indicated the need for inspection and developed suitable methods to be used. This function was felt to be important enough to have the inspection group placed under the supervision of the engineering division. The circuits are inspected for correct wiring and every solder joint is examined under a microscope. Each component is examined for correct polarity and value; it is also examined to determine that no harm has been done to it during installation. The trained inspector also observes the over-all circuit to catch any potential trouble conditions. In all cases, a sufficient number of wiring and inspection steps is included to assure that no component is buried beneath another card or component before it has been checked. Fig. 2 shows the result of a number of such steps. The completely wired regulator in this figure is ready for extensive electrical tests.

The initial electrical tests are performed at room temperature and

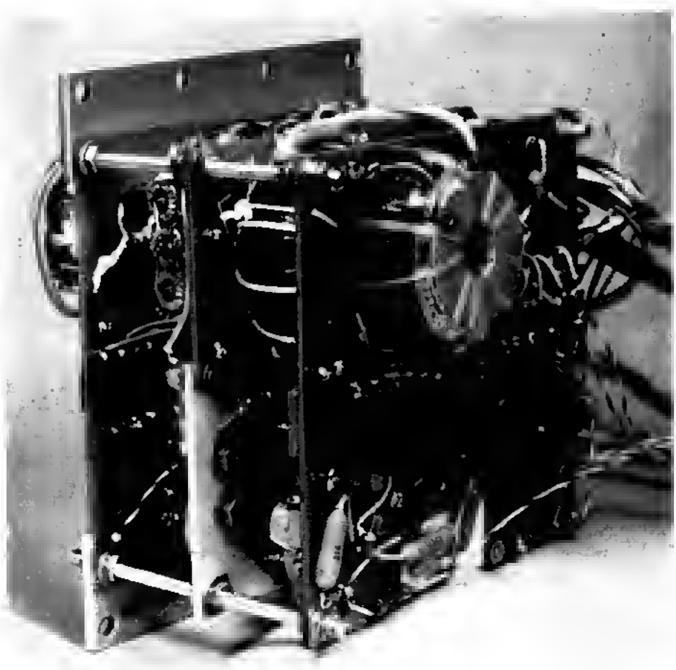

Fig. 2 — Completely wired regulator.

include any adjustments and component selection called for in the normal testing program for proper operation of the circuit. The selected components are then wired in place and inspected as indicated before. At this point, the circuit is rechecked for proper operation while it is exposed to changes in temperature, power supply voltage, and other variable quantities peculiar to that circuit. In the case of the regulator used as the example in this discussion, it is also exposed to the magnetic field of the traveling-wave tube and to a change in input voltage and output load. No vibration tests are included at this time because the unit has not yet been foamed. The foam, which encases every component, provides the necessary strength for the rather light circuit board structure.

Fig. 3 shows the regulator placed in an aluminum mold ready for foam encapsulation, and Fig. 4 shows the same unit upon completion of the encapsulating process. Special attention was given to the selection

Fig. 3 — Regulator in mold ready for foam encapsulating.

Fig. 4 — Encapsulated regulator.

of foam material and its density, to assure a reasonable compromise between supporting strength and weight.[4] Bell System experience with foam encapsulation in a missile control X-band guidance system had indicated that considerably improved mechanical reliability could be obtained by encapsulating the circuits with foam.

After foaming, the circuit is put through all the electrical tests performed prior to foaming and vibration tests with vibration magnitudes equal to those specified in the satellite acceptance test specification.[2] Because the regulator would normally operate during the launch, it was electrically tested during the vibration test. At this time, the construction and evaluation process of the unit is complete.

It can be seen that careful control of the assembly process plays an important part in establishing the high level of reliability which we believe to be incorporated in the Telstar satellite. Fig. 5 is a copy of the first of several control sheets describing the steps through which the regulator progressed on its way to completion. Most circuits have as many as 50 to 60 steps, which have all been recorded on such sheets. In each case, the person involved in a particular step signs his initials and the date, signifying the proper completion of his task. This careful record keeping assures no steps are bypassed, gives a permanent record

ROUTE SHEET POWER SUPPLY REGULATOR
B-890049 Iss. 3 (Schem)

B-133491 Iss. 2 (Assem) Board 1 of 3	Date Recv'd.	Date Compl.	Sign.
1. Assemble board as per above drawings. Serial No. F5-8515	2-8-62	2-9-62	Jaw
2. Record transistor and diode serial numbers	2-8-62	2-9-62	Jaw
3. Inspect Step 1	2-10-62	2-10-62	EJm
4. Inspect Step 2	2-10-62	2-10-62	EJm
5. Electrical Test and Adjust	2-14-62	2-14-62	AZT
6. Inspect Step 5	2-15-62	2-15-62	EJm
B-133489 Iss. 4 (Assem) Board 2 of 3			
1. Assemble board as per above drawings. Serial No. F5-8519	2-10-62	2-10-62	DTN
2. Record transistor and diode serial numbers	2-10-62	2-10-62	DTN
3. Inspect Step 1	2-12-62	2-12-62	JaF
4. Inspect Step 2	2-12-62	2-12-62	JaF
5. Electrical Test and Adjust	2-16-62	2-16-62	AZT
6. Inspect Step 5	2-18-62	2-18-62	JaF
B-133490 Iss. 7 (Assem) Board 3 of 3			
1. Assemble board as per above drawings. Serial No. F5-8523	2-14-62	2-14-62	Jaw
2. Record transistor and diode serial numbers	2-14-62	2-14-62	Jaw
3. Inspect Step 1	2-16-62	2-16-62	EJm
4. Inspect Step 2	2-16-62	2-16-62	EJm
5. Electrical Test and Adjustment	2-19-62	2-19-62	AZT
6. Inspect Step 5	2-21-62	2-21-62	EJm

ATTACHED PAPERS: Transistor and diode serial numbers

Fig. 5 — Copy of one of the regulator route sheets.

of who handled the unit, and keeps everyone constantly aware of the need for care and caution. If trouble should develop, the sheets provide a history from which the trouble can be traced and evaluated.

V. CANISTER AND ITS ASSEMBLY INTO THE SPACECRAFT

After every individual unit such as the regulator is completed, the process of mounting in the canister is started. Fig. 6 shows the canister in an early stage of assembly, together with the electronic equipment it will contain when completed. The traveling-wave tube is shown directly below the canister on the rotary table of the stand. Clearly visible are several pieces of silver-plated magnesium waveguide, and near the extreme left is the regulator which has been described in some detail in the previous section. Fig. 7 shows the same canister almost fully as-

Fig. 6 — Partially assembled canister with subassemblies.

sembled, with the traveling-wave tube mounted in the center and the waveguide surrounding it in a roughly circular arrangement. The digital, low-frequency, and VHF circuits fill in the remaining available space. The units are interconnected in nearly all cases by crimped connections. The use of connectors is kept to a minimum, because of the difficulty in determining whether a good connection has been made by the cable into each of the mating parts and whether the mating parts have been properly seated into each other. The connectors used in the canister are all tested for shorts during various mechanical manipulations of the cable and connector, and most are X-rayed. The X-ray analysis is only partially successful, however, because the inner connection is masked by the massive body of the connector.

Prior to the foaming operation, the completed canister is given an all-feature inclusive electrical test at room temperature. The only parameter changed during this test, other than the radio frequency signals, is the supply voltage. The goal of this test, as well as future tests, is not to establish a level of reliability but rather to uncover design oversights and errors made in the design process. Upon successful completion of this test, the canister is subjected to a +25°F temperature electrical test, and a +95°F* temperature electrical test. These electrical tests are not as inclusive as the initial program; however, they give a complete check of the satellite's operation.

* This value was used rather than the 40°C design value to protect the Ni-Cd cells, as explained in Ref. 5.

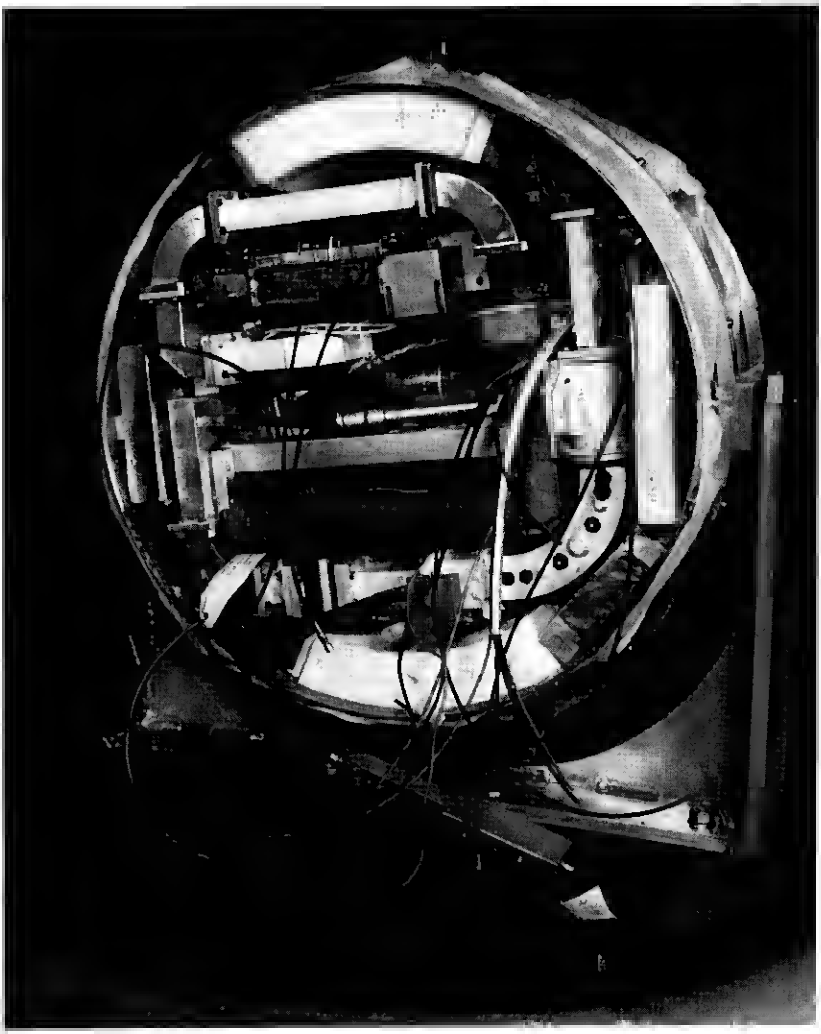

Fig. 7 — The electronics canister.

The next step is the foam encapsulation of the canister. Fig. 8 shows the canister in the last stages of the foaming process. A detailed explanation of the process is given by Shennum and Haury.[4] The properties of foam in a hermetically sealed canister in a radiation environment have been investigated; tests indicate the foam to be a stable material. During the foaming process the chief gaseous material generated is carbon

dioxide with only the slightest traces of potentially corrosive materials. Careful chemical analysis has indicated that these materials are of such small quantity that they represent no threat to the enclosed components for periods of at least several years.

Upon completion of the foaming process, the canister is subjected to a +125°F temperature soak for six hours, a 0°F temperature soak for six hours, a +25°F temperature electrical test, and a +95°F temperature electrical test. These tests are the same as the last complete tests performed on the canister prior to foaming.

Fig. 9 shows the completed canister with the domes welded in place. Before it is installed in the frame, the hermetically sealed canister is

Fig. 8 — Foam encapsulation of the canister.

Fig. 9 — Mounting of electronics canister into the frame.

checked for leaks.[4] There are a number of headers which provide electrical access to the circuitry inside the canister for such things as solar power, antenna feeds, and the radiation experiment. It is important that these headers as well as the canister dome welds be leakproof, for a complete loss of pressure in the canister when in orbit might cause permanent damage to the circuits within. Upon successful completion of the leak test, the canister is wrapped with insulating material and the thermal shutter is attached.[4] A final electrical test at room temperature assures that the canister has not been harmed during performance of the operations described.

The canister is then lowered into the frame and attached to the mounting rings, which are suspended from the frame by nylon lacing.[6] The required electrical connections are made between the external framework and the canister, the top half of the frame is attached, and the aluminum panels which support the 3600 solar cells are electrically connected and screwed into place. This completes the construction of the satellite. Prior to the detailed environmental tests which the complete satellite must undergo, an all-feature electrical test is conducted to assure that the above assembly process was complete and correct.

The detailed environmental tests include vibration on the thrust axis and on the lateral axis, and a thermal-vacuum test.[2] After every stage of the above tests, complete electrical tests are made. Each electrical test is designed to indicate that no harm was done during the environmental test. Upon completion of these tests, a successful leak test and a successful all-feature inclusive electrical test indicate that the spacecraft is of launch quality.

Fig. 9 also illustrates the working conditions which were enforced during the entire construction process. The construction area was air-conditioned; air-conditioning provided triple filtering to remove foreign particles, a 75°F* temperature, and a 35 per cent† relative humidity. In addition to the special mechanical and electrostatic air filtering, stringent controls were imposed to minimize the introduction of contaminants. These included:

1. Providing special lint-free uniforms and caps for all white area operating personnel.
2. Providing lint-free smocks and caps for all occasional personnel and visitors. Visitor entry was minimized.
3. Requiring that all personnel wash their hands and clean their shoes on each entry.
4. Cleaning all equipment to be brought into the white areas with alcohol and lint-free cloths.
5. Using paper, writing implements, and cloths that would not produce lint or dust. For example, ball point pens were used in place of pencils and dust-free crayon boards were used in place of chalk boards.
6. Mopping and dusting all white areas daily.

To monitor the effectiveness of this program, a dust count was made twice weekly and posted on local bulletin boards. The Bell System's experience in the construction of the submarine cable repeaters had

* Temperature was maintained at nominal 75°F, but was always in the range 73 to 77°F.

† Relative humidity was maintained at nominal 35 per cent, but was always in the range 30 to 40 per cent.

established the value of this sort of environment and discipline in the construction of high-reliability equipment.

VI. SUMMARY

The care exercised in assuring a spacecraft of maximum reliability has proven valuable. An unexpected level of radiation inside the canister of two orders of magnitude above the anticipated value caused command decoder circuit operation to become intermittent after four and one-half months in space with over 1100 orbits around the earth. This unexpected radiation caused one command link to become intermittent after one month of operation. The command link is completely redundant, however, so normal operation of the satellite continued. It was not until four and one-half months had passed that the other command link became intermittent and hence operation of the satellite curtailed.

It was after the second command link had failed that it was possible to make meaningful experiments on the satellite in space to determine the source of trouble. Telemetry continued to operate giving indications that the command receiver was operating normally. Exercising the command decoders with a modified command code finally operated the satellite via the command link which had failed first. This isolated the failure in that decoder to a single transistor stage.[7] The cause of the second command link failure has not been so narrowed as yet. Following the removal of power from the decoders for several passes, normal commands operated the satellite via both command links. This recovery characteristic, plus other observations at the original time of failure, indicated that the trouble was associated with a surface ionization effect on the active surfaces of transistors caused by radiation.

The telemetry unit, which has continued to operate satisfactorily, supplies information concerning the health of other parts of the system, including the communications repeater, the battery and the solar plant, and indicates that all units in the satellite are operating normally. By the use of normal commands, the Telstar repeater is again carrying communications information on an operational basis. These tests, carried on from Andover to Andover and from Andover to both England and France, indicated that the communications repeater was operating with no measurable degradation. A second period of loss at command began in late February, 1963.

VII. ACKNOWLEDGMENTS

As in any corporate effort, many people contributed to the work described in this paper. The leadership and advice of Mr. E. F. O'Neill is particularly worthy of acknowledgment.

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